Title : Method of transmitting data on multiple carriers from a transmitter to a receiver and receiver designed to implement the said method

The present invention concerns a method of transmitting data on multiple carriers from a transmitter to a receiver of a data transmission system using multiple carrier modulation, also referred to as OFDM (Orthogonal Frequency Division Multiplex). It also concerns a receiver which is particularly intended to implement the said data transmission method.

The technique of modulation on multiple carriers, referred to as OFDM, is known and consists of distributing the data to be transmitted over a large number of sub-carriers, which makes it possible to obtain a symbol time appreciably longer than the spread of the pulse response of the transmission channel between a transmitter and a receiver of the said transmission system. This technique is perfectly adapted to radio transmissions, with fixed, mobile or portable reception.

A description of a transmission system of the OFDM (Orthogonal Frequency Division Multiplex) type can be found in an article entitled "Principles of modulation and channel coding for digital broadcasting for mobile receivers", which appeared in EBU Review n° 224, pp168-190 of August 1987 in the name of R. Lasalle and M. Alard.

Such a transmission system is depicted in Figure 1 and is now described. It consists essentially of a transmitter 10 in communication with a receiver 20 by means of a transmission channel 30.

The data to be transmitted are first of all subject, in a unit 12, to a binary to signal coding which consists of a process of modulation, for example, a modulation of the QPSK (Quadrature Phase Shift Keying) type, or of the 16 QAM (16 Quadrature Amplitude Modulation) type, or of the 64 QAM type. The unit 12 delivers signals which are hereinafter referred to as modulation signals and which belong to a modulation alphabet which depends on the type of modulation used by the unit 12.

In a framing unit 13, the modulation signals delivered by the unit 12 are then put in the form of frames with possibly the insertion of reference

signals (insertion of reference symbols, insertion of distributed pilots, etc) which may prove necessary to certain processings, on the receiver side, such as synchronization processings.

The modulation signal frames delivered by the unit 13 modulate, in a unit 14, a plurality of sub-carriers with distinct respective frequencies. This modulation carried out by the unit 14 consists, for example, of the application of an inverse Fourier transform to blocks of modulation signals contained in the frames issuing from the unit 13. The unit 14 delivers signals which are hereinafter referred to as OFDM symbols.

The OFDM symbols issuing from the modulation unit 14 are subject to a digital to analogue conversion in a conversion unit 15.

All the processings implemented in the transmitter 10 are synchronized by means of a time base so that the OFDM symbols delivered by the modulation unit 14 are delivered at a sampling frequency f_e^E referred to as the transmitter sampling frequency.

It should be noted that the modulation unit 14 can provide a guard time between each OFDM symbol, which makes it possible to reduce, or even eliminate, any interference between consecutive symbols. For example, the guard time of a symbol is a replica of the end of the previous symbol and its length is chosen so that its duration is greater than that of almost all the echoes to which the transmission channel 30 is subject.

It should be noted that the data to be transmitted can previously be subject to a coding which can be of the type with convolution, of the type with convolution with an external Reed-Solomon code, of the type with codes referred to as turbo-codes or others. They can also have been subject to an interleaving which can be of the frequency type, that is to say an interleaving of the length of an OFDM symbol, or of the frequency and time type, notably when the interleaving extends over a larger number of symbols. This term “frequency and time interleaving” refers to the time-frequency representation of the OFDM signal.

Figure 2 depicts an OFDM symbol with a guard time GI of duration T_{GI} and a part containing the useful data of duration T_U. The total duration of the symbol is denoted T_S.

The analogue signal delivered by the unit 15 is then transmitted by a transmission unit 17 over the transmission channel 30 modulating a carrier at a frequency, denoted in the remainder of the description f_0^E. The frequency f_0^E is also generated by the time base 16.

It should also be noted that the transmitter sampling frequency f_e^E could be proportional to the transmission carrier frequency f_0^E.

In order to recover the transmitted data, the receiver 20 performs the operations which are the inverse of those performed by the transmitter 10. To do this, the receiver 20 has a receiving unit 27 designed to transpose into baseband the signal received from the channel 30 by means of a carrier detection signal of frequency f_0^R delivered by the time base 26. The sampling frequency f_e^R is possibly proportional to the carrier detection frequency f_0^R.

The receiver 20 also comprises an analogue to digital conversion unit 21 which is provided for delivering digital samples to the input of a unit 22 providing the demodulation of the sub-carriers which were used during the modulation performed by the modulation unit 14 of the transmitter 10.

According to one possible embodiment, the demodulation unit 22 uses a Fourier transform.

From the signal delivered by the demodulation unit 22, an estimation unit 23 performs an estimation of the modulation signals which were transmitted by the unit 12. To do this, the estimation unit 23 performs a correction of the phase shift and the amplitude changes caused by the multipath transmission channel 30.

The demodulated symbols are then decoded in a decoding unit 24 which is the dual of the coding unit 12.

All the units 21 to 24 are synchronized and, to do this, are clocked, by means of a time base 26, at a frequency which is related to a sampling frequency f_e^R, referred to in the remainder of the description as the receiver sampling frequency. In particular, the signal delivered by the conversion unit 21 is in the form of samples clocked at this receiver sampling frequency f_e^R. As for the unit 22, this demodulates blocks of samples which are grouped together within a window, hereinafter referred to as the analysis

window, determined from a clock signal at a frequency related to the said receiver sampling frequency f_e^R.

Figure 2 depicts this analysis window F positioned at a time t_n with respect to the start of the symbol under consideration.

It should be noted that, if the demodulation unit 22 ignores the data outside the analysis window, it does not carry out analysis of the samples constituting the guard time.

The estimation unit 23 can have a deframing unit 23a and a demodulation unit proper 23b. The demodulation unit 23b performs a demodulation which can be either a coherent demodulation with or without reference symbols, with or without pilots, or a differential demodulation according to the modulation performed by the coding unit 13. In the case of a coherent demodulation, an estimation of the frequency response of the channel 30 is performed in a unit 23c.

The receiver 20 of such a telecommunications system, like any telecommunications system, poses the problem of its time synchronization and, in particular, the slaving of the receiver sampling frequency f_e^R to the transmitter sampling frequency f_e^E.

When this slaving is perfectly achieved, that is to say when the receiver sampling frequency f_e^R is equal to the transmitter sampling frequency f_e^E, the processings performed in the receiver 20 are perfectly synchronized with the signal received from the transmitter 10. In particular, the position of the analysis window F used by the demodulation unit 22 can be determined so as to correspond exactly with the symbol to be demodulated.

In addition, as a result in particular of the use of a guard time, there is a certain tolerance on the position of this window.

However, the shift of the receiver sampling frequency f_e^R with respect to the transmitter sampling frequency f_e^E has three main consequences on the demodulation process:

- a loss of orthogonality between the base functions of the received signal and the base functions used for demodulation, resulting in interference between the signals modulating the different sub-carriers of the

same OFDM symbol (the distortion introduced then is generally very low and can be considered to be negligible, which is done by the invention),

- a slipping of the analysis window which results in interference between consecutive OFDM symbols when this slippage is greater than an acceptable range, and

- a phase shift between the demodulated signals of two consecutive symbols, a phase shift varying from carrier to carrier and directly related to the variation in the position of the analysis window.

Conventionally, in order to solve this problem of slaving, a feedback loop is used which slaves the receiver sampling frequency f_e^R to the transmitter sampling frequency f_e^E, using the analysis of the signals received from the transmitter. However, this solution proves to be relatively cumbersome to implement as a result in particular of the use of a voltage controlled crystal oscillator (VCXO) which is also expensive.

The aim of the present invention is therefore to propose a method which makes it possible to correct the sampling frequency shift and which facilitates the implementation of the synchronization of the receiver of an OFDM system, or which can even make it possible to dispense with the slaving of the sampling frequency.

The present invention therefore concerns a method of transmitting data on multiple carriers from a transmitter to a receiver, the said method consisting, on the transmitter side, of binary to signal coding of the data to be transmitted so as to form modulation signals, of modulating a plurality of sub-carriers with the said signals so as to form symbols, referred to as OFDM symbols, and then of transmitting, over the said channel between the said transmitter and the said receiver, the said OFDM symbols at a rate which is related to a sampling frequency referred to as the transmitter sampling frequency, and, on the receiver side, of determining, from a clock signal at a frequency related to a sampling frequency referred to as the receiver sampling frequency, an analysis window for the signal received from the transmitter so as to form a block of samples, and of estimating the said transmitted modulation signals by demodulating the said sub-carriers for the said block of samples under consideration.

According to an essential characteristic of the invention, the said estimation step is designed to correct the changes in the position of the analysis window with respect to the said transmitted signal.

Advantageously, the said estimation step consists of demodulating the said sub-carriers for the said block of samples under consideration and then correcting the effects of the transmission channel between the transmitter and the receiver, the said step of correcting the changes in the position of the analysis window consisting of estimating the phase difference between two consecutive OFDM symbols and using this phase difference during the said correction of the effects of the transmission channel between the transmitter and the receiver.

For estimating the phase difference between two consecutive OFDM symbols, the degree of shift of the sampling frequency of the receiver with respect to that of the transmitter will advantageously be estimated,

$$\delta = \delta f_e / f_e^E = (f_e^R - f_e^E) / f_e^E$$

the said phase difference between two consecutive OFDM symbols then being equal to:

$$\beta_{k,n} = 2\,\pi\, k\, \delta\, T_s / T_u$$

where T_s is the total length of the symbol under consideration and T_u its useful part, k the index of the sub-carrier under consideration and n the index of the OFDM symbol under consideration.

For estimating the phase difference between two consecutive symbols, it will also be possible to take into account the shift decision α for the position of the said analysis window delivered by a window repositioning unit, the said phase difference between two consecutive symbols then being equal to:

$$\beta_{k,n} = 2\,\pi\, k\, \delta\, T_s / T_u + \alpha . T$$

where T is the duration of a sample and α is the shift decision value expressed as a number of samples.

For estimating the phase difference between two consecutive symbols, it will also be possible to take into account solely the shift decision for the position of the said analysis window delivered by a window repositioning unit, the said phase difference between two consecutive symbols then being equal to:

$$\beta_{k,n} = 2\,\pi\,k\,\alpha.T/T_u$$

where T is the duration of a sample and α the shift decision value expressed as a number of samples.

The characteristics of the invention mentioned above, as well as others, will emerge more clearly from a reading of the following description of an example embodiment of a receiver which implements the method described above, the said description being given in relation to the accompanying drawings, amongst which:

Figure 1 is a block diagram of an example embodiment of a system for transmitting data on multiple carriers,

Figure 2 shows the structure of an OFDM symbol,

Figure 3 is a general block diagram of a receiver in a system for transmitting data on multiple carriers which is especially intended for implementing the method of the present invention, and

Figures 4a and 4b are respectively block diagrams of three estimation units according to embodiments depending on the binary to signal coding performed on the transmitter side.

The receiver 20 depicted in Figure 3 has, like the one depicted in Figure 1, an analogue to digital conversion unit 21, a demodulation unit 22, for example in the form of a Fourier transform calculation unit, an estimation unit 23, a de-interleaving unit 24 and a decoding unit 25.

The demodulation unit 22 and estimation unit 23 are synchronized by means of a time base which delivers a signal to them at a sampling frequency f_e^R, referred to as the receiver sampling frequency.

The receiver 20 also has a unit 28 provided for determining, from a clock signal delivered by a time base (not shown) and at a frequency which is related to the receiver sampling frequency f_e^R, an analysis window F for the signal delivered by the unit 21. This analysis window F is delivered to the demodulation unit 22 so as to form a block of samples to which the demodulation is applied.

According to the present invention, the estimation unit 23 carries out the demodulation of the received signal by correcting, not only the effect of the transmission channel 30, but also the phase shift which is related to the position of the analysis window F and its drift.

To do this, the receiver 20 of Figure 3 has a unit 29 which, on the basis of either the signal received by the receiver 20, or the signal output from the demodulation unit 22, delivers an estimation of the deviation δf_e of the receiver sampling frequency f_e^R with respect to the transmitter sampling frequency f_e^E.

The unit 29 can proceed in different ways depending on whether or not the receiver sampling frequency f_e^R is slaved to the carrier detection frequency f_0 of the receiving tuner.

In the first case, the unit 29 incorporates an automatic frequency control (AFC) unit (not shown) which estimates the deviation δf_0 between the carrier frequency of the transmitting tuner f_0^E and the current carrier detection frequency f_0^R of the receiving tuner and which derives therefrom an estimation of the error δf_e using the equation:

$$\frac{\delta f_0}{f_0^E} = \frac{\delta f_e}{f_e^E}$$

For example, the automatic frequency control (AFC) unit carries out an analysis, on reception, of a known symbol transmitted periodically at the start of each frame and from there gives an estimation of the shift in the carrier frequency δf_0.

It can also use two consecutive known symbols, transmitted at the start of the burst, and measure, for each carrier, the phase shift between the two received symbols.

It can also use "continuous pilots": certain fixed carriers in the frame continuously transmit known values. These continuous pilots correspond to a frequency "comb". Seeking the position of this comb on reception gives a first rough estimation of the carrier frequency phase shift δf_0. A finer estimation is then obtained by measuring the value of the phase shift between two consecutive received OFDM symbols, for the carriers of this comb.

In the second case, the unit 29 directly determines the deviation δf_e between the receiver sampling frequency and the transmitter sampling frequency from the received data.

For example, from the estimation of the time position of the analysis window t_n with respect to the useful data of the nth OFDM symbol, the unit 29 averages the variations $(t_n - t_{n-1})$ in this time position between two consecutive symbols and then determines the estimation δf_e of the sampling frequency shift δf_e by means of the following equation:

$$\delta f'_e = \frac{\overline{t_n - t_{n-1}}}{T_S} \cdot f_e^R$$

where $\overline{t_n - t_{n-1}}$ represents an average of the variations in analysis window position between consecutive symbols.

Another possibility can consist of using the phase differences on reception (which vary according to the carriers under consideration) between two consecutive known symbols. These phase shifts are in fact directly related to the deviation δf_e between the current receiver sampling frequency f_e^R and the transmitter sampling frequency f_e^E and thus make it possible to estimate it.

The receiver 20 also has a unit 30 which delivers, on the basis of the receiver and transmitter sampling frequency deviation signal delivered by the estimation unit 29, a signal representing the phase shift $\beta_{k,n}$ between two symbols as a result of the change in the position of the analysis window. This signal representing the phase shift $\beta_{k,n}$ is delivered to the estimation unit 23.

It should be noted that this signal representing the phase shift $\beta_{k,n}$ can be an estimation $\beta'_{k,n}$ of this phase shift.

It can be shown that an estimation $C'_{k,n}$ of the element of the nth OFDM symbol which modulates the sub-carrier of index k issuing from the Fourier transform used by the demodulation unit 22 can be written in the form:

$$C'_{k,n} = H_{k,n} C_{k,n} e^{-j2\pi k(T_{GI}-t_n)/T_u} = H_{k,n} C_{k,n} e^{j\theta_{k,n}}$$

where $H_{k,n}$ represents the frequency response of the channel, $\theta_{k,n}$ is the phase allocated to the element of the nth OFDM symbol modulating the sub-carrier k denoted $C_{k,n}$, T_{GI} is the duration of the guard time, T_u is the duration of the useful part of the said symbol and t_n represents the time position of the analysis window F with respect to the start of the nth symbol $C_{k,n}$ received (see Figure 2). The phase $\theta_{k,n}$ is determined by the time position t_n of the analysis window F as resulting from the following expression:

$$\theta_{k,n} = -2\pi . k(T_{GI} - t_n)$$

The estimation unit 23 consequently sees a response $\widetilde{H}_{k,n}$ of the channel 30 which is modified and which is now written:

$$\widetilde{H}_{k,n} = H_{k,n} e^{j\theta_{k,n}}$$

Thus, the result of the drift in the position of the analysis window t_n with respect to the symbol is an apparent modification of the pulse response $\widetilde{H}_{k,n}$ of the transmission channel 30.

A variation $(t_n - t_{n-1})$ in the time position of the analysis windows of two consecutive symbols therefore gives rise to a phase shift of the sub-carrier k equal to:

$$\beta_{k,n} = \theta_{k,n} - \theta_{k,n-1} = 2\pi k (t_n - t_{n-1}) / T_u$$

If this shift $(t_n - t_{n-1})$ is due only to the slow drift related to the non-slaving of the sampling frequency f_e^E, it is possible to write:

$$(t_n - t_{n-1}) = \delta T_s$$

where δ is the degree of frequency shift and is given by the following equation:

$$\delta f_e = f_e^R - f_e^E = - f_e^E \delta$$

The value of the phase shift of the sub-carrier k for the nth symbol is therefore equal to:

$$\beta_{k,n} = 2 \pi k \delta T_s/T_u$$

This expression can also be written, considering this time the number of samples N in the analysis window and the number of samples Δ corresponding to the guard time:

$$\beta_{k,n} = 2 \pi k \delta (N + \Delta) / N$$

where $N = T_u . f_e^E$ and $\Delta = T_{GI}. f_e^E$

It should be stated that T_s represents the total length of the OFDM symbol. This gives:

$$T_s = T_u + T_{GI}$$

In the embodiment depicted in Figure 3, the receiver 20 has a unit 31 which is provided for delivering a window advance or retard signal α expressed, for example, as a number of samples. To do this, it estimates, for example, the pulse response of the transmission channel and then determines the time position of the first peak of this response. This position

makes it possible to estimate the position t_n of the analysis window with respect to the useful part of the symbol (see Figure 2).

Depending on the value of this position, the unit 31 decides to advance or move back the current analysis window by one or more sample time units represented by the signal α which is then delivered to the unit 28 in order to determine a new analysis window.

The signal α delivered by the unit 31 makes it possible to readjust regularly the analysis window used by the unit 22 for calculating the Fourier transform. In the case of a burst or a frame of relatively small length, this readjustment can be performed at the start of the frame (or the burst) with no consequence on the demodulation of the data. In the contrary case, it will cause a phase shift (variable depending on the carrier under consideration), completely analogous to the phase shift caused by the regular slippage of the analysis window due to the error on the frequency f_e^E.

The unit 30 can also take into account the part of the shift which results from an intentional action on the time base 28 by means of the window positioning signal α delivered by the unit 31. In this case, the variation between consecutive symbols of the position of the analysis window $(t_n - t_{n-1})$ can be written in the form :

$$t_n - t_{n-1} = \delta Ts + \alpha T$$

where $\delta = -\delta f_e'/f_e^R$ and T is the duration of a sample ($T = 1/f_e^R$).

Thus, the phase shift $\beta_{k,n}$ of the sub-carrier k for the nth symbol is equal to :

$$\beta_{k,n} = 2\pi k\,(t_n - t_{n-1}) / T_u = 2\pi k\,(\delta Ts + \alpha T)/T_u$$

For example, for $\delta = 10^{-5}$, $N/\Delta = 4$, $k = 3405$, a phase shift $\beta_{3405} = 0.26$ radians is obtained.

According to another embodiment, not depicted, the unit 30 delivers a signal representing the phase shift $\beta_{k,n}$ between two consecutive OFDM symbols which is related solely to the window advance or retard signal α.

In this case, the variation between consecutive symbols of the position of the analysis window $(t_n - t_{n-1})$ can be written in the form :

$$t_n - t_{n-1} = \alpha T$$

where T is the duration of a sample ($T = 1/f_e^R$) and α is the window advance or retard signal delivered by a unit 31.

Thus, the phase shift $\beta_{k,n}$ of the sub-carrier k for the nth symbol is equal to :

$$\beta_{k,n} = 2\,\pi\,k\,(t_n - t_{n-1})\,/\,T_u = 2\,\pi\,k\,\alpha\,T/T_u$$

The precise way in which the estimation unit 23 proceeds in order to correct, not only the effect of the transmission channel 30, but also the phase shift which is related to the position of the analysis window and its drift, depends on the type of demodulation used by the demodulation unit 23 (see Figures 1 and 3): synchronous with one reference symbol or a number of consecutive reference symbols, synchronous with distributed pilots, or differential.

Figure 4a depicts a block diagram of a symbol estimation unit 23 of the type performing a coherent demodulation of a modulated signal having, generally transmitted at the start of the frame or burst, at least one reference symbol. This estimation unit 23 receives the signal $Y_{k,n}$ issuing from the demodulation unit 22 depicted in Figure 3 and delivers to the decoding unit 24 the estimated signal $C^{'}_{k,n}$ corresponding to the element modulating the kth sub-carrier of the nth OFDM symbol. It also receives from the unit 30 depicted in Figure 3 the estimated value of the phase shift between two consecutive symbols $\beta^{'}_{k,n}$.

The unit 23 has a demodulator 230 to which is supplied an estimation of the frequency response of the channel $\widetilde{H}_{k,n}$ determined by an estimation and updating unit 231. The latter has a unit for estimating the response of the channel 231a which makes it possible to estimate the response of the channel for the reference symbol or symbols ($n = 0, 1, ..., t-1,$ where t is the number of consecutive reference symbols). It also has an updating unit 231b

which determines the response of the channel by means of the following recursive equation :

$$\widetilde{H}_{k,n} = \widetilde{H}_{k,n-1} e^{j\beta_{k,n}}$$

The demodulator 230 then estimates the element modulating the kth sub-carrier of the nth OFDM symbol by means of the following equation :

$$C'_{k,n} = \left(\widetilde{H}'_{k,n}\right)^{-1} Y_{k,n}$$

In the case of a coherent demodulation designed to perform the demodulation of a signal having distributed pilots, the estimation unit 23 first estimates the response of the transmission channel where the pilots were transmitted (in the time-frequency plane of the OFDM signal) and then interpolates, time-wise and frequency-wise, in order to estimate the frequency response of the channel $H_{k,n}$ at all frequencies and for all symbols. To do this, the estimation unit 23 can have an interpolation filter which is for example of the two-dimensional type (time + frequency).

It should be stated that the pilots are data which are transmitted in the OFDM frame in a distributed manner in the time-frequency domain. These transmitted data are known by the receiver.

The variations in the phase shifts $\theta_{k,n}$ on the frequency axis are not an inconvenience. This is because the frequency response of the channel $H_{k,n}$ itself varies rapidly as a function of the frequency, and an interpolation filter is capable of taking these variations into account. On the other hand, as a result of the values of the frequency response of the channel $H_{k,n}$ not being supposed to vary too quickly along the time axis, an interpolation filter can be disrupted if the drift of the sampling frequency δf_e is too great.

Figure 4b depicts a particular embodiment of an estimation unit 23 designed to perform the demodulation of a signal having distributed pilots. This estimation unit 23 has a unit for estimating the response of the channel 231 itself composed of a unit for estimating on pilot 231c intended to estimate the frequency response of the channel solely on the pilots. These different estimations are stored in a memory 231d, and then rephased in a

unit 231e, which receives from the unit 30 (Figure 3) the value of the phase shift between consecutive symbols $\beta'_{k,n}$. The estimation unit 231 also has an interpolation unit 231f which, on the basis of the rephased signals for channel estimation on the pilots, delivers an estimation of the frequency response of the channel $\widetilde{H}_{k,n}$ for all carriers k and all instants n.

The estimation unit 23 of Figure 4b also has a unit 232 intended to introduce a delay corresponding to that introduced by the unit 231. It also has a unit 233 which introduces into the delayed data issuing from the unit 232 a phase shift equal to the value $(\theta'_{k,n} - \theta'_{k,n-p})$ that is :

$$\theta'_{k,n} - \theta'_{k,n-p} = \sum_{j=0}^{p-1} \beta'_{k,n-j}$$

where p is the latency of the interpolation unit 231f. This makes it possible to rephase the delayed data with the estimations supplied by the unit 231, in view of the drift of the sampling frequency δf_e and the adjustments of the estimation window during this delay. The values of the phase shifts $\beta'_{k,n-j}$ are supplied by the unit 30.

The rephased data are supplied to an equalization unit 230 which then delivers the demodulated symbols to a decoding unit 24 (Figure 3).

Figure 4c depicts an estimation unit 23 of the type for demodulating signals modulated by differential modulation. It should be stated that, in this case, the useful data $D_{k,n}$ were modulated according to the following equation:

$$C_{k,n} = D_{k,n} C_{k,n-1}$$

The corresponding demodulation is performed in the unit 230. The estimation unit 23 has a delay unit 234 which delays by one OFDM symbol (of length T_s) the input signal issuing from the demodulation unit 22 and a unit 235 which calculates the conjugate of the delayed symbol. The signal demodulated in the unit 230 can then be written as follows:

$$Y_{k,n} Y^*_{k,n-1} = \left(H_{k,n} H^*_{k,n-1}\right) e^{j\beta_{k,n}} D_{k,n} + noise \approx \left|H_{k,n}\right|^2 e^{j\beta_{k,n}} D_{k,n}$$

This signal is supplied to a phase shift unit 236 receiving from the unit 30 the value of phase shift $\beta'_{k,n}$ between consecutive symbols. The unit 236 then delivers a demodulated signal of the form:

$$D'_{k,n} = Y_{k,n} Y^{*}_{k,n-1}\, e^{-j\beta'_{k,n}} \approx \left|H_{k,n}\right|^{2} D_{k,n}$$